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Validation of F-Scan pressure sensor system: A technical note

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Abstract—This study performed a quantitative validation on a recently developed pressure sensitive transducer system, the F-Scan sensor system. The results indicate that the sensor is adequate for determination of pressure distribution under contact conditions with soft materials. The linear response of the sensor was up to 1.7 MPa with good homogeneity throughout sensor cells. However, the sensor is sensitive to surface conditions, loading speeds, and temperature. Variations also exist from sensor to sensor. In order to have accurate measurement, calibration was recommended in actual clinical or experimental conditions prior to use, including surface contact conditions, loading speeds, and temperature environment. In addition, this sensor system is not suitable for hard surface contact such as plexiglas.

Key words: *F-Scan sensor system, pressure, validation.*

INTRODUCTION

In the last few years, a new pressure sensor system, F-Scan (Tekscan, Inc., South Boston, MA), has been developed to measure pressure distribution between two contact objects (1,2). This technique is particularly useful for plantar pressure measurement in clinic evaluation and gait analysis (3–6). The advantages of F-Scan are its dynamic response to loading and multiple sensor cells to determine the pressure distribution. However, studies to date have been qualitative; that is, they have consisted of the rough assessment of pressure distribution because of limited calibrations of the sensor and the complexity of the intrinsic properties of sensor materials.

This sensor system consists of an ultra thin (0.18 mm) two-layer sheet. Each layer is built on a flexible substrate made of Mylar, a polyester film. An electrically conductive ink is printed on the film and coated with a pressure-sensitive, resistive ink, in such a fashion that parallel rows of electrodes on the top layer face parallel columns of electrodes on the bottom layer through the resistive ink. The interceptions of the rows and columns construct the pressure-sensing cells. Due to the change of resistance of the pressure-sensitive resistive ink, when load is applied to the sheet, the electrical signal output from this system will respond accordingly.

This system responds not only to the applied pressure, but can also be influenced by other variables, such as surface contact hardness conditions, creeping of the coated resistive ink under pressure, and temperature. Linearity and homogeneity of the sensor cell response are also not clearly defined. These issues must be addressed before the F-Scan pressure sensor system can be used to quantitatively assess contact pressure. This study investigates the response of sensors to specific variables to provide guidelines for quantitative use of the F-Scan pressure system.

METHODS

The F-Scan sensor used in this study was a footwear sensor designed to measure plantar pressures of the foot. The sensor insole consists of 955 individual pressure-sensing cells, evenly distributed at 5.05 mm intervals. Through specially designed data acquisition

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software, sensor output was recorded on a 486 computer.

Except for the evaluation of temperature on sensor output, the experiments were performed on a servo-hydraulic material test system (MTS 810, MTS Systems Corporation, Minneapolis, MN) that applied compression force to either the entire insole sensor or individual cells. The insole sensor was sandwiched between two 6.4 mm thick firm insole foams (plastizote), backed by two 12.7 mm thick aluminum plates. Uniform pressure was applied to the sensor through the rigid plates and soft foam by a compression force from the MTS machine. Uniform pressure was confirmed by moving the sensor between the foams and plates to different positions that revealed nearly identical sensor output contours. Since the sensor temperature may rise, causing output variations due to heat generation within the electric circuit and insulation by the foam, temperature was monitored with a digital thermometer and a thermosensor needle placed near the central region of the F-Scan insole sensor.

Evaluation of the linearity and homogeneity of cell responses was performed at five static loading levels: 2,225, 4,449, 6,674, 8,898, and 11,123 Newtons (N), equivalent to a uniform pressure of 0.048, 0.096, 0.145, 0.193, and 0.241 Megapascal (MPa, or $N/m^2 \times 10^6$), respectively, applied to the sensor. From these five levels, the linear regression was performed on each cell as

$$p = c_0 + c_1 x \qquad [1]$$

where p is the pressure in MPa, x is sensor output represented by the raw electronic signals varying in level from 0 to 255, and c_0 and c_1 are two regression coefficients in MPa. The linear response to the pressure was evaluated by R^2 for each cell. The homogeneity was examined by calculating the mean and standard deviations (SD) of the two coefficients in Equation 1 throughout the cells. After loading for 60 s, sensor output for the static loading conditions was recorded for 3 s.

The maximal pressure that could be applied to the entire sensor was only 0.241 MPa, which is roughly equal to the body weight when standing on one foot (75 kg body weight and 311 mm^2 foot contact area). In order to see whether the sensor is capable of covering pressures that one might find under human feet, additional tests were performed on a few selected cells in the forefoot area. Compression force was applied to single cells to examine the linearity between the pressure input and sensor output in a wider pressure range. The loading area of a single cell is 31.2 mm^2. Five loading levels were 8.9, 17.8, 35.6, 53.4, and 71.2 N, which were equivalent to the pressure of 0.285, 0.571, 1.141, 1.712, and 2.282 MPa on the tested cell, respectively. The maximal pressure 2.282 MPa corresponded roughly to 4.6 times body weight when standing on the forefoot (75 kg body weight and 150 mm^2 forefoot contact area).

Influence of surface contact hardness on sensor output was examined with a uniform pressure of 0.193 MPa on three surface conditions: 1) soft-soft surface condition: two foam insoles; 2) soft-hard surface condition: one foam insole; and 3) hard-hard surface condition: two 1 mm thick rigid plastic sheets were inserted between the foams and the sensor to create a hard surface contact condition on both sides of the sensor.

Because of possible effects of resistive ink creeping under pressure on sensor output, dynamic response of the sensor to the loads was evaluated from two aspects: static and dynamic. Under static load, a constant load of 8,898 N was applied for 120 s, and the output as a function of time was determined. Under dynamic load, the effect of loading speed on sensor output was studied under two dynamic conditions: loading to 11,123 N within 1 s (loading speed of 0.241 MPa/s), and loading to 11,123 N within 10 s (loading speed of 0.0241 MPa/s).

For evaluation of temperature effects on sensor output, the bottom foam was removed and the sensor was placed directly on an aluminum plate precooled to below 0 °C in a freezer. During the test, the plate was placed on an electric heater with a flat surface that allowed proper heat transfer to the sensor through the plate. An 18.2 kg aluminum block was placed on the top plate within a contact area of 5,280 mm^2 to provide a local 0.034 MPa pressure on the central region of the sensor. A thermosensor needle and digital thermometer were used to monitor the temperatures in this region. Output was recorded while the temperature varied from 10 to 45 °C.

Individual curve fitting for each cell and linear equation was used to check whether the results from all cells could be represented by a single line. Two coefficients were determined by averaging the coefficients from two dynamic and one static loading conditions. The pressure and overall contact force were also calculated from this single curve, fitting at the tested five levels.

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Output variations among different F-Scan sensors were tested on three sensors (two additional sensors) under dynamic loading to 11,123 N within 1 s (loading speed of 0.241 MPa/s). We examined the calculation variations among different sensors with linear regression as described in Equation 1.

We calculated means and SD throughout the cells by standard methods. For the tests on the same sensor, we used the repeated measures analysis of variance (ANOVA) with Tukey test to detect differences. For the tests among the different sensors, ANOVA with Tukey test was used.

RESULTS

The F-Scan insole pressure sensor system had a uniform response to the static loading throughout all the cells (R^2=0.979±0.016, mean±SD). The sensor response also showed a uniform distribution with c_0=−0.041±0.017 and c_1=0.012±0.002. Further evaluation on individual cells demonstrates that they have the same linear response up to 1.7 MPa (**Figure 1**). The temperature monitored for the static loading tests did not vary dramatically (21.6±0.2°C).

Sensor output highly depends on the contact surface hardness (**Figure 2**). Theoretically, pressure-sensitive cells should respond to the uniform pressure equally. However, both the mean and SD of sensor output increased with increased surface hardness. For soft-soft surface condition, sensor output demonstrated a nearly uniform distribution as 19.93±2.81. When one foam was withdrawn from the top (the soft-hard contact), the uniformity was less and both the mean and SD increased slightly (20.10±3.97). For the hard-hard surface condition, the output showed significant variability (58.80±17.93). The mean output was three times greater under the hard surface condition than with soft-soft contact. For the hard surface condition, the SD was 6.38 times greater than with soft-soft contact. The hard surface results were very significantly different from those derived from the other two conditions ($p<0.001$).

Sensor output also shows the resistive ink creeping under a constant pressure (**Figure 3**). The average output over all the cells slightly increased from 19.4 to 20.5 within 120 s, and this tendency was continuous afterwards. The means of the linear regressions of two dynamic loads over all the cells show similar regression coefficients to static loading at five loading magnitudes. For a loading speed of 0.241 MPa/s (R^2=0.982±0.006), c_0=0.002±0.004 and c_1=0.012±0.001. For a speed of 0.0241 MPa/s (R^2=0.983±0.008), c_0=0.000±0.003 and c_1=0.012±0.001. For the three loading conditions, both c_0 and c_1 were statistically different ($p<0.01$). The

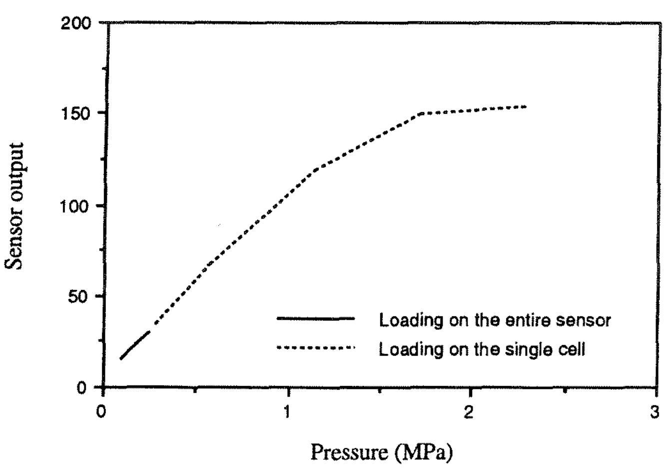

Figure 1.
A typical cell response to loads: the linear response is shown to 1.70 MPa.

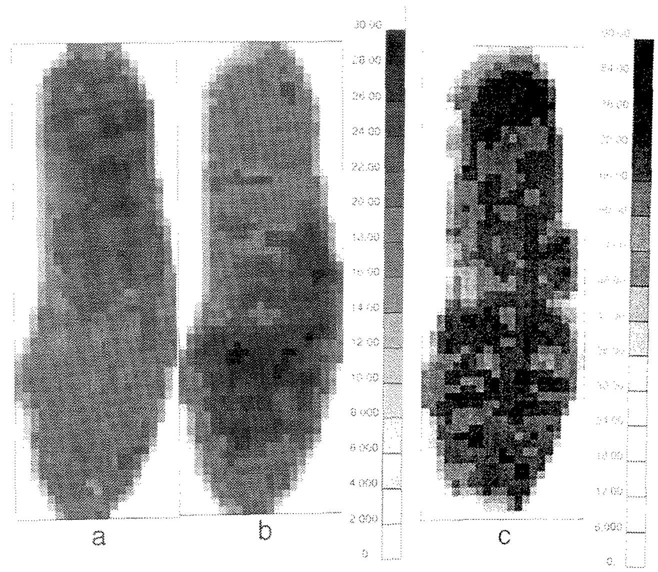

Figure 2.
Distribution of sensor output under a uniform pressure of 0.193 MPa with three surface conditions: a) Soft-soft; b) Soft-hard; c) Hard-hard. The output shows a nearly uniform distribution in a), the uniformity is partially destroyed as SD increased in b), and is completely destroyed with significantly increased mean and SD in c).

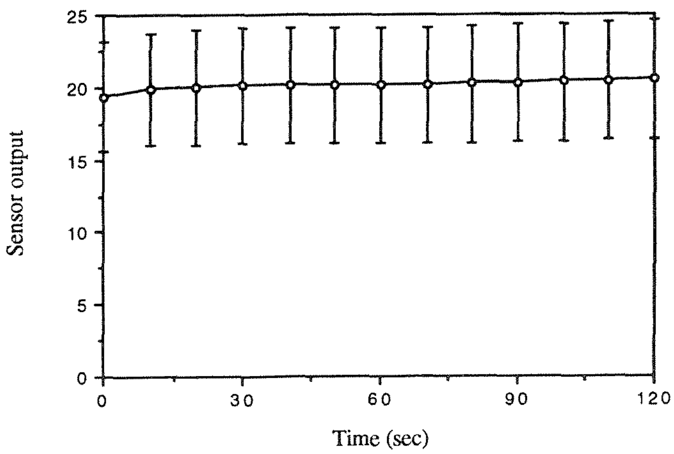

Figure 3.
Average sensor output over all the cells under a constant pressure of 0.193 MPa within 120 s. The output increase from 19.4 to 20.5 indicates slight creeping of intrinsic pressure-sensitive resistive ink.

Table 1.
Pressure results from linear regression using individual curve fittings for static load and two dynamic loads.

Applied Pressure	Static load	Dynamic load I	Dynamic load II
0.048	0.045±0.006 (92.9%)	0.058±0.005 (120.1%)	0.052±0.004 (108.1%)
0.096	0.107±0.008 (111.5%)	0.094±0.009 (97.8%)	0.104±0.007 (108.1%)
0.145	0.147±0.011 (101.5%)	0.131±0.010 (90.7%)	0.150±0.007 (103.9%)
0.193	0.186±0.032 (96.7%)	0.187±0.016 (97.3%)	0.186±0.009 (100.5%)
0.241	0.242±0.008 (100.5%)	0.244±0.012 (101.5%)	0.233±0.013 (96.8%)

Static load=0.193 MPa for 120 s; dynamic load I=0.241 MPa/s; dynamic load II=0.0241 MPa/s; results as mean±sd; percentages in parentheses are the ratio of the calculated pressure to the applied pressure.

Table 2.
Overall contact force calculated from individual curve fittings for static load and two dynamic loads.

Applied force	Static load	Dynamic load I	Dynamic load II
2225	2069	2675	2405
4449	4961	4354	4815
6674	6773	6052	6935
8898	8601	8658	8613
11123	11186	11291	10772

Static load=0.193 MPa for 120 s; dynamic load I=0.241 MPa/s; dynamic load II=0.0241 MPa/s; units: N.

calibrated pressure measurements and overall contact forces at five levels are shown in **Tables 1** and **2.** Errors up to 20.1 percent were observed at lower loading levels, but the maximal error was only 3.2 percent at the high loading level (0.241 MPa).

As expected, sensor output was related to temperature (**Figure 4**). The most dramatic change occurred above 30 °C, when sensor output increased from 7 at 30 °C to 20 at 45 °C, while from 10 to 30 °C the total change was 3 (from 4 to 7).

Using averages of the two coefficients from all three loading speed conditions over all cells ($c_0=-0.013$ and $c_1=0.012$) increased the maximal error at lower loading levels up to 55.0 percent (**Tables 3** and **4**). At higher loading levels, the error also increased to 16.9 percent at 0.2408 MPa.

Testing the two additional sensors showed a $c_0=-0.054\pm0.047$ and $c_1=0.011\pm0.003$ for sensor 2 ($R^2=0.962\pm0.027$), and $c_0=-0.041\pm0.017$ and $c_1=0.012\pm0.002$ for sensor 3 ($R^2=0.980\pm0.016$). There were statistically significant differences in c_0 and c_1. The results at the five loading levels also show good representation of the applied pressure (**Table 5**).

DISCUSSION

The F-Scan sensor system has been used in clinic and biomechanical studies because of its dynamic response to loading and multiple sensor cells to determine pressure distribution. This study performed quantitative analyses to validate this system under various pressures, loading speeds, and temperature conditions. The important findings are summarized as follows:

Sensor output highly depends on contact surface hardness: on hard surfaces, significant errors in output exist. The F-Scan pressure sensor cannot be used to determine the loading pressure on hard surface. Clinically, this means that the sensor has to contact with soft materials or tissues such as sole and accommodative inlays. For soft contact surfaces, sensor output provides excellent linear correlation to the pressure load up to a pressure level of 1.712 MPa. The output also demonstrates homogeneity of the sensor with a minimal variation between cells under uniform pressure throughout the sensor.

Sensor output is sensitive to temperature, especially above 30 °C. However, temperature variation was

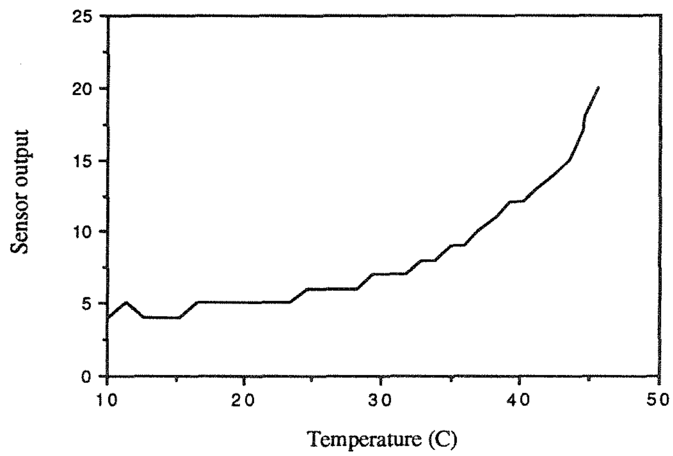

Figure 4.
A typical cell response to temperature variation from 10 to 45 °C. Notice that the dramatic change occurred above 30 °C.

Table 3.
Pressure results from linear regression using a single curve fitting (c_0=−0.013, c_1=0.012) for static load and two dynamic loads.

Applied Pressure	Static load	Dynamic load I	Dynamic load II
0.048	0.075±0.013 (155.0%)	0.043±0.008 (88.8%)	0.040±0.007 (83.8%)
0.096	0.126±0.018 (131.3%)	0.078±0.013 (81.2%)	0.092±0.014 (96.0%)
0.145	0.178±0.025 (123.3%)	0.115±0.017 (79.4%)	0.139±0.017 (96.1%)
0.193	0.230±0.033 (119.3%)	0.172±0.029 (89.1%)	0.176±0.023 (91.3%)
0.241	0.281±0.052 (116.9%)	0.228±0.028 (94.6%)	0.224±0.032 (92.8%)

Static load=0.193 MPa for 120 s; dynamic load I=0.241 MPa/s; dynamic load II=0.0241 MPa/s; results as mean±sd; percentages in parentheses are the ratio of the calculated pressure to the applied pressure.

Table 4.
The overall contact force from a single curve fitting (c_0=−0.013, c_1=0.012) for static load and two dynamic loads.

Applied force (N)	Static	Dynamic 11123 N/s	Dynamic 1112.3 N/s
2225	3448	1978	1865
4449	5837	3613	4270
6674	8226	5302	6419
8898	10614	7933	8127
11123	13003	10525	10326

Static load=0.193 MPa for 120 s; dynamic load I=0.241 MPa/s; dynamic load II=0.0241 MPa/s; units: N.

Table 5.
Pressure results of linear regression using individual curve fittings for three tested sensors in MPa.

Applied Pressure	Sensor 1	Sensor 2	Sensor 3
0.048	0.058±0.005 (120.8%)	0.059±0.005 (122.9%)	0.053±0.009 (110.4%)
0.096	0.094±0.009 (97.9%)	0.089±0.017 (92.7%)	0.083±0.015 (86.4%)
0.145	0.131±0.010 (90.3%)	0.121±0.021 (83.4%)	0.144±0.017 (99.3%)
0.193	0.187±0.016 (96.9%)	0.188±0.025 (97.4%)	0.189±0.014 (97.9%)
0.241	0.244±0.012 (101.2%)	0.244±0.017 (101.2%)	0.248±0.021 (102.9%)

not due to electrical circuit heating. Thus, when used in the clinical conditions, the temperature factor has been considered. The sensor should only be used for a short period of time if temperature is above 30 °C.

The sensor system is also sensitive to the loading speed. As shown in **Table 2,** significant errors can occur even if the coefficients were determined from averages of different loading speed trials. This suggests that careful calibration of the F-Scan sensor system should be performed under similar dynamic conditions to the tests. In addition, errors up to 20.1 percent were found at lower loading levels due to limited cell resolution. This may affect sensor accuracy in clinical or experimental uses at those levels.

Responses of individual sensors to loading pressures are slightly different. Calibration of individual sensors prior to use is recommended in actual testing situations.

Many variables upon which sensor output depends can be explained by the resistive ink contact interface at the microstructural level (**Figure 5**). The gap at the ink contact interface significantly varies from cell to cell. Under hard surface conditions, the back surfaces (A,D) contact to a relatively stiff plate, the gap at the interfaces (B,C) is basically preserved during loading. The resistance of the cells that have more peak-to-peak contact will be higher than that of the cells that have more peak-to-valley contact. For soft contact surfaces, the gap at interface (B,C) can be substantially eliminated because of the flexibility of the back surfaces (A,D). Cell resistance is more homogeneous throughout the sensor on soft contact surfaces. In addition, ink creeping under pressure and rising temperature may increase the interface contact area and therefore change sensor output.

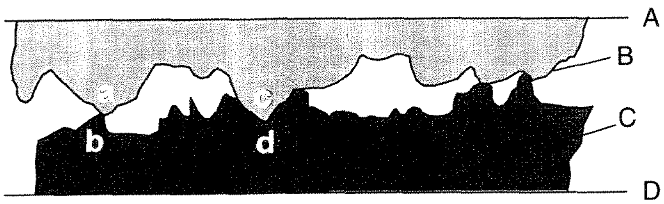

Figure 5.
Illustration of the microstructure of the resistive ink contact interface. A=back surface of the top layer; B=ink interface of the top layer; C=ink interface of the bottom layer; D=back surface of the bottom layer. The interface contact could be from peak-to-peak (points a and b) to peak-to-valley (points c and d). Under the hard-hard surface condition, the back surfaces A and D contact relatively stiff plates, preserving the interface gap. The resistance of cells with more peak-to-peak contact will be higher than that of cells with more peak-to-valley contact. For soft-soft contact, the gap can be substantially eliminated because of the flexibility of the surfaces A and D: the cell resistance becomes much more homogeneous.

This study provides quantitative guidelines in using the F-Scan pressure sensor system under well-controlled loading conditions. Future studies should further evaluate accuracy and reliability of the system under clinical conditions. Factors that need to be considered have been identified here, including the contact surface, loading conditions, and temperature. Additionally, reexamination of the F-Scan sensor system is also necessary whenever it is upgraded.

CONCLUSIONS

This study suggested that the F-Scan pressure sensor is adequate for determination of pressure distribution under contact conditions with soft materials. However, the sensor is sensitive to surface conditions, loading speeds, and temperature. Variations also exist from sensor to sensor. In order to have accurate measurement, calibration was recommended in actual clinical or experimental conditions prior to use, including surface contact conditions, loading speeds and temperature environment. In addition, the sensor system is not suitable for hard surface contact, such as rigid plastic sheeting.

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Sensing stability and dynamic response of the F-Scan in-shoe sensing system: A technical note

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Abstract—The objective of this study was to gain a better understanding of the F-Scan to determine its appropriate clinical application. Vertical pressure was applied to a sensor foil over the range of 10–80 kPa with or without the intervention of 0.2–0.8 mm thick felt. Sensor sensitivity reached a maximum without the felt, and decreased with increasing felt thickness, stabilizing at 48–74% of the maximum level when felt thickness exceeded 0.4 mm. This sensitivity change was caused by the slight difference in thickness of sensing areas from that of non-sensing areas. Dynamic response time was delayed by a mean of 0.32 s. Although the cause of this dynamic response delay remains unclear, it was considered to be inappropriate for accurate dynamic measurements. Therefore, rather than using F-Scan measurement to accurately obtain actual values, it should be used for relative comparisons of the plantar pressure distributions under constant conditions.

Key words: *foot, gait analysis, insole sensors, orthotic devices, plantar pressure.*

INTRODUCTION

The F-Scan in-shoe sensing system (Tekscan, Inc., Boston, MA) displays pressure distribution between the sole and the insole by using a 0.15 mm sensor foil placed inside the shoe (1). Although this epoch-making device has many areas of clinical application (2), there are many unresolved questions regarding with this system and other in-shoe sensing systems (3–8).

According to the manufacturer, the sensor accuracy level was less than ±5 percent of the range with calibration, the rise time of the sensor was 5 μs[1]. Furthermore, F-Scan version 3.611 or later has adopted a special calibration procedure to compensate for differences between the F-Scan's force values and the vertical component of the floor reaction force measured by the Kistler force plate less than ±10 percent at any walking velocity without force plate measurements (9,10).

The high accuracy level of this sensor may be preferable for common clinical tests, but the specific conditions under which this high accuracy is valid remain unclear. The fast rise time of the sensor may be very effective in all sorts of dynamic measurement, but our clinical experiences have shown that the F-Scan tends to underestimate the actual force values in normal walking; this tendency has suggested a relatively slow dynamic response compared to force plates. The unreliability of F-Scan's second peak force values also has been pointed out by other researchers (8). Although detailed information on the mechanism of the special calibration procedure (the Baumann compensation) is unavailable, bipedal recordings of a minimum of six steps (three lefts, three rights) must be made for this

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